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Environmental footprints of disposable and reusable personal protective equipment – a product life cycle approach for body coveralls

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ABSTRACT

Body coveralls, often made of single-use plastics, are essential Personal Protective Equipment (PPE) and, along with masks, are widely used in healthcare facilities and public spaces in the wake of the recent COVID-19 pandemic. The widespread use of these body coveralls poses a significant threat to terrestrial and aquatic ecosystems, given their polluting nature and disposal frequency. Therefore, it is necessary to promote the adoption of alternatives that increase the safe reusability of PPE clothing and reduce environmental and health hazards. This study presents a comparative *Cradle-to-Grave* Life Cycle Assessment (LCA) of disposable and reusable PPE body coveralls from a product life cycle perspective. A comprehensive life cycle inventory and LCA framework specific to Indian conditions have been developed through this study. The LCA is performed as per standard protocols using SimaPro software under recipe 2016 (H) impact assessment method. Six midpoint impact categories *viz*. Global Warming Potential, Terrestrial Acidification, Freshwater Eutrophication, Terrestrial Ecotoxicity, Human Carcinogenic Toxicity, and Water Consumption are assessed, along with Cumulative Energy Demand. Results suggest that reusable PPE improves environmental and human health performance in all the impact categories except water consumption. Sensitivity analysis reveals that replacing conventional electricity with solar energy for PPE manufacturing and disposal will provide additional environmental benefits. The findings can help the medical textile industries, healthcare workers, and policymakers to make environmentally informed choices.

1. Introduction

The accelerated demand for plastic products in developing countries like India is threatening ecosystems from its fossil-based production to its unsustainable disposal processes (Shekhar et al., 2022). The recent COVID-19 pandemic has exacerbated this issue by promoting rapid growth in disposable PPE, which provides the first line of defence against the novel Coronavirus amongst HCWs.

The COVID-19 pandemic was declared a Public Health Emergency of International Concern (PHEIC) by the World Health Organization (WHO), given the grave contagiousness of the virus across continents. A developing country like India, having a dense population coupled with a high prevalence of comorbid health conditions, showed a sudden spike in the infection rate that burdened the healthcare system (Neto et al., 2020). The Government of India, along with the state governments, came forth with combined prophylactic efforts to flatten the curve of infection rate through social distancing norms, periodic lockdowns, and assured usage of PPE for HCWs and caretakers (MoHFW, 2020). The Infection Prevention and Control (IPC) measures set down by WHO mentioned the “appropriate and rational use of PPE and hand hygiene by health workers associated with SARS-CoV-2 virus”, identifying PPE as the first line of defence. As the infection rate escalated, it parallelly led to a dramatic surge in demand for PPE by HCWs and even the general public (Liang et al., 2021) for infection prevention and control (Singh N et al., 2020) while depleting the reserve stockpiles. India embarked on a journey from scarcity to abundance, producing 0.45 million body coveralls per day from 1100 manufacturers (PIB, 2020), emerging as the 2nd largest producer in the world. This rapid scale-up, however, caused upstream supply chain disruptions and downstream waste disposal problems (Klemeš et al., 2020).

The PPE body coveralls are protective clothing that uses polypropylene plastics as raw materials, providing flexibility and resistance to water and virus. However, these are generally single-use and non-recyclable and may take years to decompose (Silva et al., 2020). The discarded PPE body coveralls and other infected PPE materials course through the waste streams from hospitals, healthcare facilities, quarantine centres, and even households (Liang et al., 2021) to over-burden

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Nomenclatures

Abbreviations	*Full forms/ Definitions*
PPE	Personal Protective Equipment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
CED (LHV)	Cumulative Energy Demand (Lower Heating Value)
HCW	Healthcare Workers
PHEIC	Public Health Emergency of International Concern
WHO	World Health Organization
MoHFW	Ministry of Health and Family Welfare
IPC	Infection Prevention and Control
SARS CoV- 2	Severe Acute Respiratory Syndrome Coronavirus
PIB	Press Information Bureau
BMW	Biomedical Waste
UNEP	United Nation Environment Programme
CAW	COVID-19 Associated Waste
CPCB	Central Pollution Control Board
UV	Ultraviolet
MSW	Municipal Solid Waste
GHG	Greenhouse Gas
POP	Persistent Organic Pollutants
MPs	Microplastics
CDC	Center for Disease Control and Prevention
NIH	National Institute of Health
ISO	International Organization for Standardisation
ASTM	American Society for Testing and Materials
BIS	Bureau of Indian Standards
EVA	Ethyl Vinyl Acetate
PE	Polyethylene
CNC cutter	Computer Numerical Control cutter
LDPE	Low Density Polyethylene
HDPE	High Density Polyethylene
EO	Ethylene Oxide
PV	Photovoltaic
FU	Functional Unit
SMS	Spunbond Meltblown Spunbond
HCF	Healthcare Facilities
CICR	Central Institute for Cotton Research
BRAI	Biomass Resource Atlas of India
IOCL	Indian Oil Corporation Limited
CBWTF	Common Biomedical Waste Treatment Facility
IGIMS	Indira Gandhi Institute of Medical Sciences
PP chips	Polypropylene chips
GSM	Gram per Square Meter
MCU-5	Long staple cotton variety
PET	Polyethylene Terephthalate
P_{Life}	Product Life phase
EoL	End of Life phase
GWP	Global Warming Potential
1,4- DCB	1,4- Dichlorobenzene
NABARD	National Bank for Agriculture and Rural Development
SDG	Sustainable Development Goals
BCI	Better Cotton Initiative
NFSM	National Food Security Mission

the waste management infrastructure in many developing countries, which is generally ill-equipped to satisfactorily handle even routine solid waste (Klemeš et al., 2020). Data on healthcare waste generation rates worldwide have shown that biomedical waste (BMW) has soared from 0.5 kg per bed per day in the pre-COVIDtime to 3.4 kg per bed per day during the pandemic (UNEP, 2020). India alone produced 45,954 tonnes of COVID-19-associated waste (CAW) from the start till May 2021 (CPCB, 2021), with the healthcare waste generation rate shooting up from 0.5 kg to 2.5–4 kg per bed per day during the pandemic (Ramteke and Sahu, 2020). Further, the composition of this additional waste makes its management and treatment challenging, given the dynamic changes induced by CAW's physical and biological properties (Kothari et al., 2021).

The healthcare sector acts as a perpetrator and a victim of environmental pollution. The plastic-based PPE coveralls' life cycle, from their production processes to their disposal as waste, significantly impacts all components of the earth - air, water, and land (Kutralam-Muniasamy et al., 2022). Several studies have confirmed the presence of toxic chemical additives like plasticisers, UV stabilisers, flame retardants, phthalates, antioxidants, organophosphate esters, bisphenols, and other endocrine-disrupting chemicals in the plastic manufacturing process that endanger the environment through toxic leachates (Kutralam-Muniasamy et al., 2022) and release of GHGs during its production (Rizan et al., 2021; Kumar et al., 2020).

Disposable PPE waste is no exception (De-la-Torre and Aragaw, 2021; Klemeš et al., 2020; Silva et al., 2021; Kutralam-Muniasamy et al., 2022), generally following two pathways – landfill and incineration, both emitting pollutants to the environment (Silva et al., 2020). These pathways are predominant in many Indian cities and parts of Asia due to the fear of infection, precluding any recycling option (Dharmaraj et al., 2021). Open burning in landfills has been a recurrent practice for CAW plastic waste disposal along with municipal solid waste (MSW), which leads to space crunch and toxic pollution (Silva et al., 2021) while putting the ragpickers at risk of infection (Sharma et al., 2020). The chemical additives and toxic monomers in the PPE disintegrate in the landfill, leaching into the soil and polluting the groundwater over time (Kutralam-Muniasamy et al., 2022). Disposal of contaminated PPE waste in landfills is often fatal to wintering birds and other organisms that rely on landfill waste for their food. Various seagull species hovering over these landfills have shown decreased reproduction caused by chemical toxicity (Silva et al., 2021). The massive unmanaged dumps contribute to the production of greenhouse gases like CH_4 and CO_2 in the atmosphere, which starts forming 2–3 years after disposal (Silva et al., 2021).

The global share of plastic waste in MSW landfills is 12%, with plastic from PPE waste accounting for 3.5% (Water Footprint India, 2022). The inflow of plastic waste from PPE has increased the load on incineration facilities – a method of hazardous waste treatment suggested by WHO during COVID-19 – in countries like India and China (Vanapalli et al., 2021). It also releases extensive GHGs, and persistent organic pollutants (POPs) like dioxins and furans into the atmosphere while burning (Batterman, 2004). The synthetic polymers of the PPE waste are equally hazardous in the aquatic environment as the action of wind and water flows quickly disperses these into urban spaces and coastal zones (Kothari et al., 2021; Kutralam-Muniasamy et al., 2022), where they persist for years, eventually disintegrating into microplastics (MPs) and nano plastics. The MPs released in freshwater (Kumar et al., 2021) and marine environments bioaccumulate through aquatic organisms into the human food web (Klemeš et al., 2021). About 20% of marine crustaceans and other aquatic organisms have been reported to have MPs in their bodies (Ray et al., 2022). Boucher et al. (2020) highlighted that around 4.8–10 Mt of macro and microplastics are released into the environment every year, and this number has increased during the pandemic. Another worry in PPE manufacturing is the energy-intensive nature of the textile industry, comprising many heavy plants for different processes that use a significant amount of energy (Hasanbeigi and Price, 2012). Energy is one of the most prominent and cost-intensive inputs (Koç and Kaplan, 2007). In India, the textile industry is dependent on coal, furnace oil, and diesel for fueling the high electricity-demanding textile processes (Palanichamy and Babu, 2005), releasing massive amounts of GHGs into the atmosphere.

Given the detrimental effects of disposable PPE in the ecosystem (Do Thi et al., 2021), there is a pressing need to shift towards a more environment-friendly alternative that closes the loop of the circular economy. While reductions and recyclability are discussed extensively, the option of reusability has not been explored sufficiently among the universal 3Rs principle for plastic waste management (Klemeš et al., 2021). With the massive inflow of disposable PPE body coveralls posing a key challenge to the healthcare waste management system, reusable body coverall has become a promising alternative with a better environmental profile of its disposal pathway (Vozzola et al., 2020; McQuerry et al., 2021; Van den Berghe and Zimmer, 2011). The Center for Disease Control and Prevention (CDC) also strongly recommended the shift toward reusable PPE over disposable as a solution to manage the surge capacity during the pandemic (CDC, 2020). Reusable PPE body coverall is made of tightly woven fabric that is chemically finished with silver coatings to improve its liquid and viral barrier properties (Karim N et al., 2020) and can be laundered after each use via multiple washing cycles (10–15 times) (Thakur et al., 2021) to get rid of the virus that persists on its surface for 2–3 days (NIH, 2020). They are made of different fabric combinations in different parts of the world like woven cotton fabrics in parts of Africa, woven polyester fabrics in the US or the most commonly used-cotton-polyester blend fabrics in India and several other countries. Reusable PPE is also inert in the landfill environment whereas the disposable PPE material has a middle non-woven layer of melt-blown fabric made of polypropylene which releases loads of micro and nano-plastics (Kutralam-Muniasamy et al., 2022).

Despite these hazards, disposable PPE made of polypropylene dominates the global market, accounting for 80% of the healthcare fabric. Performance analysis of disposable PPE shows that it meets the standard requirements of protections like the synthetic blood penetration test and hydrostatic penetration test (Karim N et al., 2020), slightly better than the reusable PPEs in a high-contamination risk environment. However, disposable PPE is preferred by HCWs for long-term use over reusable ones due to their high breathability and comfort (McQuerry et al., 2021). Reusability also raises concerns about a higher water footprint due to multiple washes. But it is expected that, in the long run, there will be a shift in favour of the reusable PPE market, provided it is more economical (Hicks et al., 2021) and environmentally beneficial. Disposable PPE can cost more than reusables if their purchase frequency, high treatment cost as biohazard waste, and environmental externalities are factored in (Singh S et al., 2021).

An environmental and human health impact analysis will contribute to the debate between disposable and reusable PPE body coveralls in healthcare and public discourse. LCA is an important decision-support tool for policymakers, producers, and consumers in assessing a product's cradle-to-grave environmental and human health impact. For disposable and reusable PPE body coveralls, a thorough comparative assessment of their life cycles, including their raw material acquisition, manufacture, supply chain, use, and end-of-life phases, is required. It can then facilitate the transformation of the healthcare waste management sector, along with integrated improvements in the manufacturing of PPE textiles, strengthening the circular economy approach and encouraging ecosystem conservation (Kumar et al., 2020).

In India, LCA studies to assess the environmental impact of individual PPE items like body coveralls are limited primarily due to i) lack of standard protocol for LCA of PPE body coverall, ii) non availability of India-specific inventory in standard database such as Ecoinvent which is Europe centric, iii) Furthermore, collection of required inventories has also been challenging due to the COVID-19 pandemic. Considering these limitations, this study presents a comparative LCA study of disposable and reusable PPE body coveralls from a product life cycle perspective while building an LCA framework for environmental and human health assessment of body coverall in India which is novel in nature. The LCI generated in this study through personal interviews (of medical textile industries, healthcare industries, waste management facilities), mathematical modelling, database and literature reference is comprehensive in nature which is another significant contribution of this work. The LCI is produced and reported for every life cycle stage of the body coverall throughout its manufacturing, usage, and disposal stages with details of flux of all direct and indirect materials, resources, energy and water, to assess a range of environmental and human health indicators, which can also be applied in similar LCA studies in other regions. Furthermore, hotspot and contribution analysis as well as scenario and sensitivity analysis conducted in this study will enable relevant stakeholders to adopt alternative ways to minimize the overall environmental and human health impacts of body coverall.

2. Product description: PPE body coveralls

After face masks and gloves, body coveralls are identified as the second most widely used PPE by the HCWs, and even the general public (McQuerry et al., 2021). It protects the wearer's body against contact with contaminated fluids and droplets in hazardous and life-threatening environments during episodes of contagious disease outbreaks. The fabrics used for coveralls need to be durable, lint-free, breathable, air permeable, and biocompatible for the wearer, depending on whether they are disposable or reusable. For a coverall to be suitable for protection against the COVID-19 virus, it should comply with stringent international standards, such as the European International Organization for Standardisation (ISO) standard and the American Society for Testing and Material (ASTM) standard. The Bureau of Indian Standards (BIS) issued the Indian Standard IS: 17,423:2020 for PPE body coveralls during the COVID-19 pandemic, on the lines of the ISO and ASTM standards. It is based on four test parameters – the Synthetic Blood Penetration Test, Viral Permeability Test, Hydrostatic Pressure Test, and Breathability Test – to determine the fabric's medical suitability for mass manufacturing.

Body coverall is a sewn product made to act as a medical PPE and they are generally of two kinds depending on their fabric type and usability patterns - disposable and reusable coverall. The donning and doffing of the coveralls require training and supervision to provide effective viral protection to HCWs and people. The process of body coverall garment construction and packaging are common for both types of coveralls as shown in Fig. 1 while differing only in their fabric material. Both the coveralls are seam-sealed by overlaying tape on the garment joints to make them resistant to viral penetration and potential contamination. According to the coverall fabric type, the seam seal tape is 0.15 mm thick having a weight of 0.95 gm/square cm and can be made of either fabric + Ethyl Vinyl Acetate (EVA) glue or Polyethylene (PE) + EVA glue. Thus, the seam seal tapes must also undergo the same certification tests (Thakur et al., 2021). Furthermore, a figure showcasing how a PPE body coverall looks is given in Fig. 1 of the supplementary file and the manufacturing processes of each coverall's type fabric material are shown in detail in Figs. 2 and 3 of the supplementary file.

3. LCA methodology

The present study uses a cradle-to-grave attributional LCA for a comparative environmental and human health impact analysis of the market-representative disposable and reusable PPE body coveralls in India. The single-use disposable ones are made up of polypropylene non-woven fabric, whereas the reusable ones are woven cotton polyester blend fabric that is washable and can be reused an average of 15 times (Thakur et al., 2021).

3.1. Defining the scope

The environmental aspects and potential health impacts of the two products are studied throughout their life cycle, from the acquisition of raw materials required to their manufacturing, usage, and end-of-life

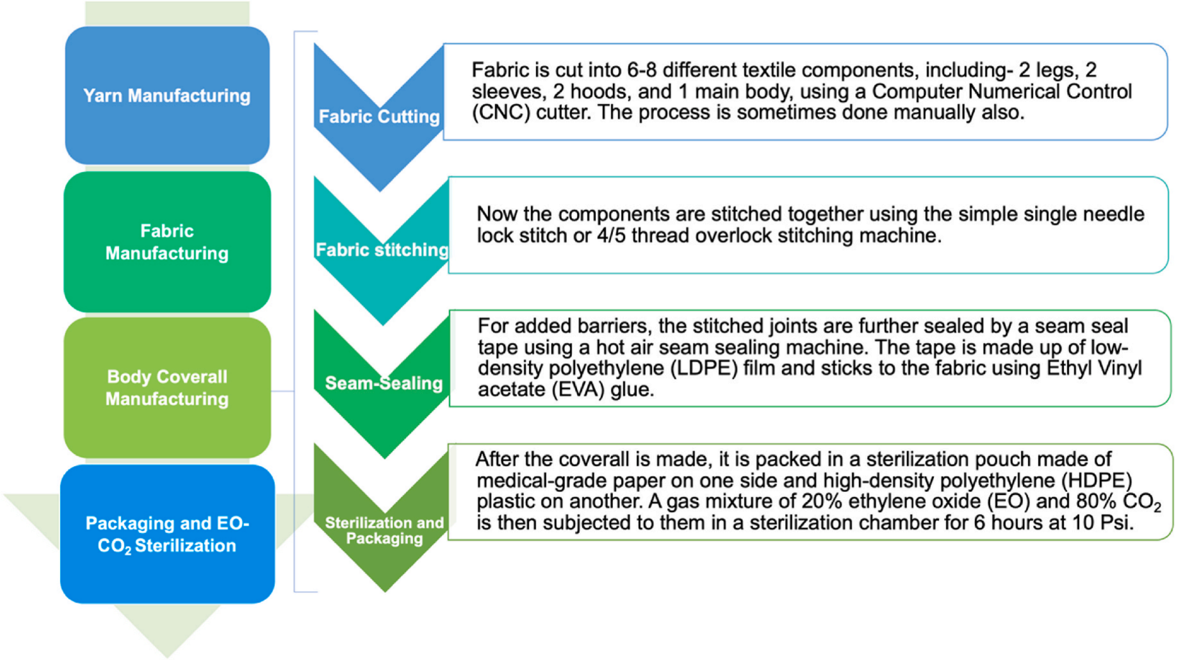


Fig. 1. Steps involved in the manufacturing of PPE body coveralls.

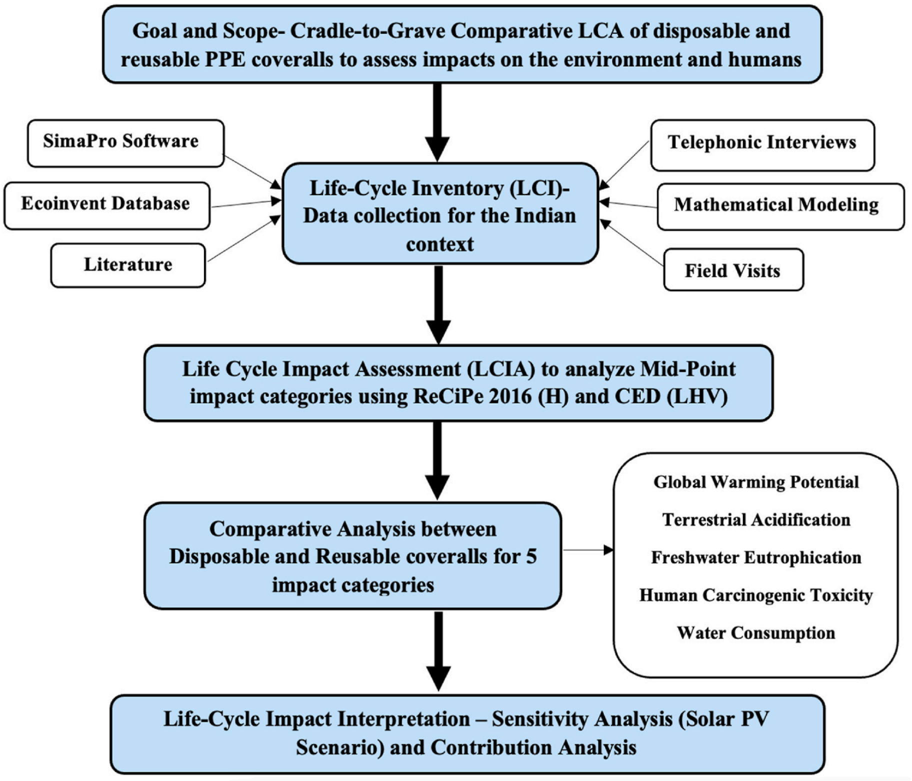


Fig. 2. LCA Framework developed according to the Indian context.

treatment phases. LCA is performed using standard ISO 14040/14044 protocol. SimaPro 9.2 LCA software is used for the analysis of the two products. All four stages of LCA were followed, including defining a goal and scope of the study, building an LCI, conducting a Life Cycle Impact Assessment (LCIA), and Interpretation of the results. The intended audience of this study includes the pharmaceutical and medical textile industries, healthcare organisations, the public, policymakers and LCA practitioners.

The LCI is derived from the relevant literature, government reports, expert consultation, telephonic interviews with industry personnel, the Ecoinvent global database and mathematical modelling. Due to a lack of India-specific LCI, the study uses a descriptive LCA framework to represent the Indian scenario. Inventories generated through this work are expected to help similar future studies. The framework is shown in

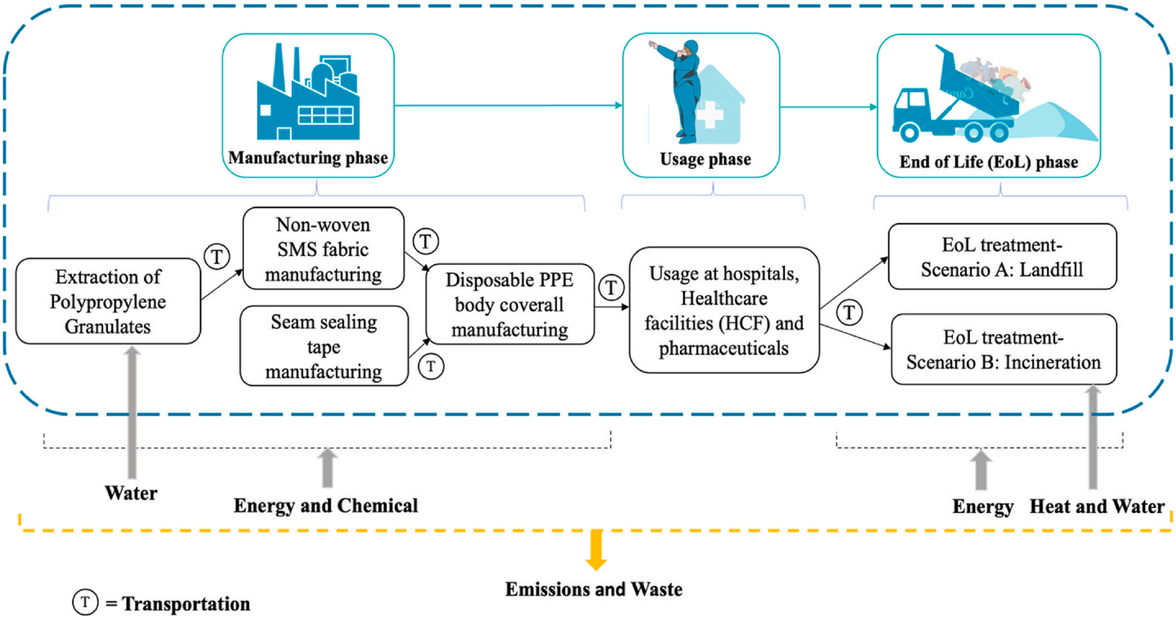


Fig. 3. System boundary for LCA of disposable PPE body coverall.

Fig. 2.

3.1.1. Functional unit (FU)

The FU is taken as 1000 kg for each type of body coverall. A single disposable and reusable PPE body weighs 0.250 kg and 0.369 kg, respectively. Hence, the number of disposable body coveralls manufactured according to the FU is 4000 and the number of reusable body coveralls manufactured according to the FU is 2710. The FU is taken as 1000 kg for both products because of the ease of calculations and representations of the outcomes. Another major reason is that each PPE body coverall is very less in wt. (0.250 kg and 0.369 kg), so for its environmental and health impact indicators to be measurable and quantified, FU is taken as 1000 kg.

The reference flow for 1000 kg (FU) of disposable PPE is 743.36 kg of polypropylene chips, 246 kg of LDPE Polyethylene film for lamination (the meltblown layer of SMS disposable non-woven fabric), 62.49 kg of Polyethylene LDPE film for seam seal tape and 41.66 kg of Glue EVA to paste seam seal tape. The reference flow for 1000 kg (FU) of reusable PPE is 540 kg of Cotton fabric, 291 kg of polyester fabric, 42.92 kg of Polyethylene LDPE film for seam seal tape and 28.61 kg of Glue EVA to paste seam seal tape. Thus, the total reference flow for 1000 kg of FU disposable PPE is 1093.51 kg, whereas the total reference flow for 1000 kg of FU disposable PPE is 902.53 kg. Some material losses accounts for the difference in total reference flow value from the FU of 1000 kg.

The system boundaries for both the product of comparison are shown in Figs. 3 and 4. Ancillary materials like packaging films and tapes are included in this system boundary but not represented.

3.1.2. Impact allocation

Impacts are partitioned by allocating the inputs and outputs of the

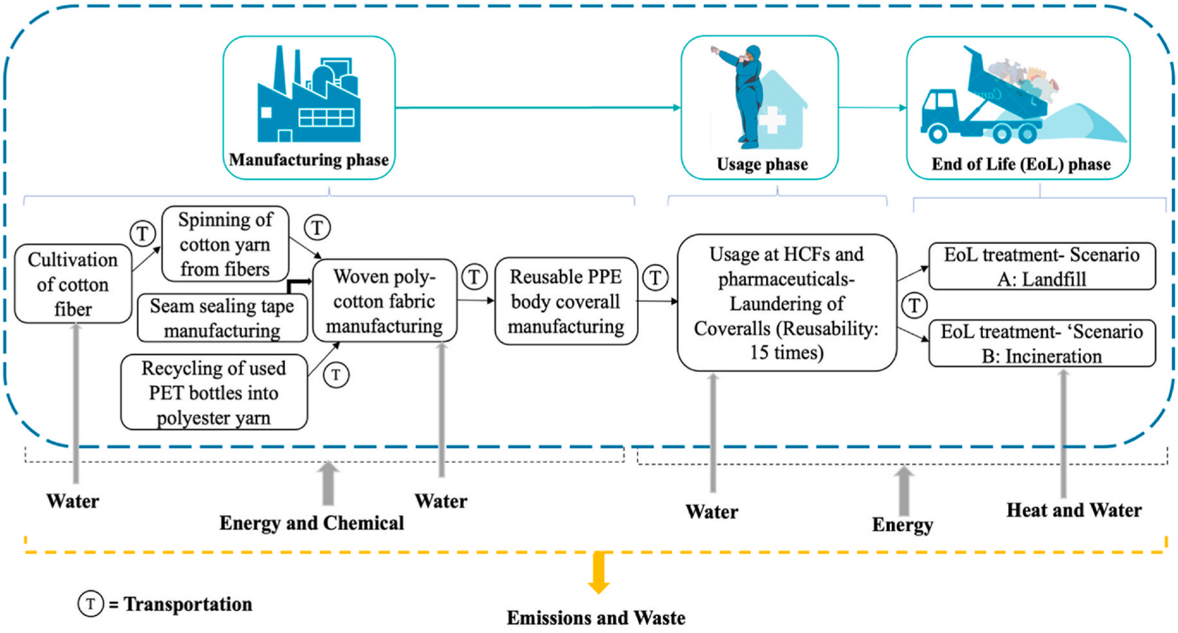


Fig. 4. System boundary for LCA of reusable PPE body coverall.

process to different products and co-products. There are three impact allocation methods - mass allocation, energy allocation, and economic allocation. Here the inputs and outputs of a process are assigned to all its products and co-products according to their mass, heating value, and market values, respectively.

In the cotton cultivation process of reusable PPE products, cottonseed and cotton stalk are co-products, apart from cotton fibre – the primary product. The economic allocation method is appropriate here since prices can describe the attributes of a complex system that physical criteria like mass and energy cannot measure. Moreover, it shifts the environmental burden to the main product, the cotton fibre in the cultivation process, from the low-value co-products (Taylor et al., 2017) like cottonseed and cotton stalk, which may be co-produced in high quantity (Ardente and Cellura, 2012) in disposable PPE products, there are no co-products in any process. The economic allocation of products in the cotton cultivation stage is shown in Table 1.

3.1.3. Data assumptions

Data gaps were encountered for the input raw materials and energy consumption for some processes. For instance, difficulties in assessing the input of heavy machinery in the manufacturing process were overcome by extrapolating electricity consumption data of textile machines in similar studies published outside India. The polyester fibers used for reusable coverall fabric were considered to be recycled from PET bottles, as around 50% of polyester fibres in India stems from recycling (The Hindu, 2017). It was also assumed that the distance between different stages in the same state or city would be 25 km (50 km round-trip), and transport of raw materials between different states would be of 500 km (like transport of polypropylene chips from Reliance or Indian Oil Corporation Limited (IOCL) to the manufacturing units in Tamil Nadu). Energy consumption, primarily in the form of electricity and diesel for irrigation and diesel for transportation, was calculated according to standard mathematical models (Hiloidhari et al., 2021). The calculated data is included in the inventory, and the calculations are presented in the supplementary file Tables 10 and 11.

3.2. Life cycle inventory (LCI)

This step is the backbone of any LCA study, as the quality and robustness of the LCI define the impact assessment.

3.2.1. Data collection

The data inventory for various life cycle stages of the PPE body coverall was acquired through literature surveys, field visits, the Ecoinvent database, mathematical modelling and importantly by conducting personal telephonic interviews with medical textiles industries, healthcare experts and waste management facilities in the state of Tamil Nadu, India, as it was one of the major PPE manufacturing states certified by the Ministry of Textiles. A field trip to the Common Biomedical Waste Treatment Facility (CBWTF) of the IGIMS (Indira Gandhi Institute of Medical Sciences), Patna (Bihar, India) was made to understand the basic procedure for incinerating PPE coveralls and the material and energy consumption of the facility. The raw data collected was validated by tallying multiple sources before converting these into standard, comparable units. These units of material and energy inputs were then linked to the functional units of the products. The operational procedures followed for LCI are guided by ISO standard 14041.

Table 1
Economic allocation of cotton cultivation stage.

Products	Price[a] (USD/kg)	Economic allocation factor (%)	Source
Cotton fiber	1.69	83	CICR, India
Cotton seed	0.32	16	CICR, India
Cotton stalk	0.02	1	BCI, 2020
Total	2.03	100	

[a] 1 USD ~ 76.5 INR in April 2022.

3.2.2. LCI as per functional unit

The LCI has been prepared as per the FU (1000 kg) and presented in Tables 2 and 3.

3.3. Life Cycle Impact Assessment (LCIA)

LCIA is the phase of an LCA study where the inputs and outputs of the elementary flows obtained from the data inventory are assessed and translated into mid-point and end-point impact indicators related to human health, environment and resource depletion. The LCIA is performed using two methods as discussed below.

3.3.1. ReCiPe 2016

In the present study, Midpoint (H) V1.03/World (2010) H version of the ReCiPe method is used where H represents the Hierarchist model which is mostly used for consensus and scientific models. Only mid-point impact categories were studied because detailed impact parameters of the input were necessary for the comparative assessment of the present LCA study.

3.3.2. Cumulative Energy Demand (Lower Heating Value)

The CED LCIA method in SimaPro software help in investigating the source and share of energy use throughout the life cycle of a product or service. This is useful in prioritising the energy-saving potentials of the best energy source throughout the complex *cradle-to-grave* life cycle.

3.4. Interpretation phase

A sensitivity analysis is performed to analyse which outcome measures are sensitive to the variation of the input parameters. In our study, sensitivity analysis of energy demand is done using CED and 100% Solar energy scenario analysis. It helps us to know which parameter will be interesting to investigate in the LCA study. The energy grid input was changed from the fossil fuel-based Southern India- Tamil Nadu (TN) electricity grid to the Global 20 MW high voltage rooftop solar energy grid to study the change in impacts if the energy source will be substituted with 100% solar electricity.

Contribution analysis is also done to know which input parameter of a particular process or stage is contributing most to pollution and toxic contamination of the environment.

4. Results and discussion

Textile industry is one of the most polluting sectors of the world, accounting for a significant amount of GHG emissions, water consumption, and landfill waste in the environment (European Parliament, 2019). The industry manufactures apparel in bulk at an affordable price but there are significant environmental externalities. Medical textiles and equipment are major contributors of pollution from this industry. The plastic-based disposable medical equipment has a very short life and high disposal frequency, which involves long-term environmental degradations in their manufacturing and end-of-life processes. The fossil-based raw materials and hazardous chemicals used during the production process release a huge amount of atmospheric GHGs emissions, toxic contaminants, and microplastics in the biosphere, threatening life.

In line with the above context, the findings as well as the analysis of data obtained by performing the LCA are discussed below in detail. It describes the LCIA as well as the interpretation phases of the present LCA study.

Table 2
Life cycle inventory in the Indian context as per FU of disposable PPE coveralls.

Input	Life cycle stage	Quantity	Unit	Note	Source
Material/Chemical					
Polypropylene (PP) chips	Fabric manufacturing stage	743.36	kg	1% PP loss	Pers. Comms.
Polyethylene LDPE film for lamination (PE lamination machine)		246	kg	15 GSM (g m^{-2})	
Glue EVA for lamination		82.3	kg	5 GSM	
Polyethylene LDPE film for seam seal tape		62.49	kg	8.68 m tape in 1 Coverall	
Glue EVA for seam seal tape		41.66	kg		
Recycled packaging film (LDPE) for tape		1.3	kg	For 694 rolls of seal tapes	Assump.
Carton Box of recycled flute material for tape storage		10.84	kg		Assump.
Recycled packaging film (LDPE) for fabric		15	kg		
Medical grid paper (65 GSM) (Cellulose fiber) for sterilisation pouch	Body Coverall manufacturing stage	36	kg	0.15 m^2 is the area of one pouch	India mart, 2020
HDPE polyethylene plastic (15 GSM) for sterilisation pouch		9	kg		
Carton Box of recycled flute material for PPE coverall storage		111.12	kg		
Ethylene Oxide (EO) gas for PPE sterilisation (EO-CO_2 sterilisation chamber)		21.2	kg	20% content in the gas	CDC, 2016
CO_2 gas for PPE sterilisation		84.8	kg	80% content in the gas	CDC, 2016
HDPE polyethylene plastic for storing waste	Treatment stage-Landfill	8	kg		Assump.
Caustic Soda (NaOH)	Treatment stage-Incineration	2.82	kg		
Alum (Aluminium Sulphate)		0.84	kg		
Ferric Chloride		0.014	kg		
Electricity/Fuel					
Electricity for SMS (Spunbond-meltblown-spunbond technology machine) non-woven fabric formation- 45 GSM (Gram per square metre)	Fabric manufacturing stage	522.56	kWh	7100 unit t^{-1}	
Electricity for polyethylene lamination		98.4	kWh	0.3 unit kg^{-1}	
Electricity required to manufacture seam seal tape		22.91	kWh		India mart, 2020
Electricity required for refrigerated storage of tapes		17.3	kWh		Industry website
Electricity required for converting the fabric into PPE coveralls (Machinery- CNC cutter, single needle lock stitch or 4/5 thread overlock stitching machine, Hot air seam sealing machine)	Body Coverall manufacturing stage	270.2	kWh	1 unit for 15 coveralls on a 16-machine line	Pers. Comms.
Electricity required for cutting and sealing pouches		28	kWh		
Electricity required in sterilisation chamber		355.5	kWh		Pers. Comms.
Diesel consumed in the round-trip transportation in different processes		0.56	kg	575 km travelled on one side	Transport model
Diesel consumed on a round-trip (25 + 25 km)	Treatment stage-Landfill	1.55	kg		Transport model
Electricity required to run the incineration unit	Treatment stage-Incineration	80.7	kWh	The plant runs 12–13 h a day	Field visit,
Diesel consumed to burn the waste		17	kg	OCEMS data not reported	Pers. Comms.
Electricity required to treat water in Effluent treatment plant		8.7	kWh		Field visit
Summary of total material input		**1488.84**	**kg**		
Summary of total energy (electricity) input		**1404.27**	**kWh**		
Total fuel input (other than electricity)		**19.11**	**kg**		
Input from nature					
Total land area required	Treatment stage-Landfill	**0.045**	**m^2**		Field visit
Total water utilised in quencher chamber	Treatment stage-Incineration	**10,000**	**l**		Field visit

4.1. Comparative impact assessment of disposable and reusable PPE body coverall

A total of 18 mid-point impact indicators were assessed by the software, and they were analysed to study the multidimensional impacts of PPE coveralls on the environment, human health and resource depletion (Supplementary file Table 1). Out of them, 6 impact indicators are discussed in detail.

1) Global Warming Potential (kg CO_2 eq) – Effect on air
2) Terrestrial Acidification (kg SO_2 eq) – Effect on land
3) Freshwater Eutrophication (kg P eq) – Effect on water quality
4) Terrestrial Ecotoxicity (kg 1,4-DCB) – Effect on terrestrial organisms
5) Human Carcinogenic Toxicity (kg 1,4-DCB) – Effect on humans
6) Water Consumption (m^3) – Effect on water quantity

The life cycle of the coveralls was divided into two phases, *viz.* Product life (P_{Life}) and End-of-Life (EoL) phases as shown in Fig. 5.

The P_{Life} phase of the coverall comprises the impacts and emissions originating from the fabric and body coverall manufacturing stages, usage stage along with the transportation connecting all the stages. The transportation and usage stages were clubbed together into the P_{Life} phase (Fig. 5) and not compared separately in the life cycle due to the following reasons.

- The disposable PPE coverall had no usage stage emissions due to its single use, while the reusable coverall had low emissions due to minimal inputs in the usage stage for 15 laundry washes per coverall as per the FU.
- The transportation in the P_{Life} phase consumed a negligible amount of diesel as per the FU in connecting the subsequent stages

Table 3
Life cycle inventory in the Indian context as per FU of reusable PPE coveralls.

Input	Life cycle stage	Quantity	Unit	Note	Source
Material/Chemical					
Polycotton fabric (Cotton: Polyester blend~ 65:35 ratio)	Fabric Manufacturing stage			For 2710 coveralls = 831 kg polycotton fabric	
Cotton fabric (65%)		540	kg	100% cotton fibre converts to 78% fabric = 1.27 multiplier = 691 kg cotton fiber required for FU	BCI, 2020
Cotton seed of MCU 5 hybrid variety	Cotton cultivation stage	21	kg		The Hindu, 2017
Fertiliser (N, P, K)		112; 56; 56	kg		NFSM, 2020
Micronutrient (Zn, Mn, B)		14; 14; 4.2	kg		NFSM, 2020
Biofertilizer (Azospirillum; Azophos)		0.84; 0.84	kg		NFSM, 2020
Weedicide (Pendimethalin)		1.4	kg		
Lubrication oil		1.2	kg		Mathematical modelling
Polyester Fabric (35%)	Polyester yarn manufacturing	291	kg	Fabric to yarn multiplier = 1.11 due to losses of yarn to make fabric	Shen et al., 2010
Used PET (Polyethylene terephthalate) bottles required to recycle into polyester fiber (Pellet extrusion machine)				498 kg of PET bottles required	
Recycled packaging film (LDPE) for fabric cover	Polycotton fabric manufacturing	13	kg		Pers. Comms.
NaOH industrial Soap in washing		0.017	kg		
Hydrogen peroxide (H_2O_2) used for bleaching		0.024	kg		
Caustic Soda		27.63	kg		
Alum		8.1	kg		
Ferric Chloride		0.135	kg		
Polyethylene LDPE film for Seam seal tape	Body coverall manufacturing	42.92	kg		Same as disposable (Pers. Comms.)
Glue EVA for seam seal tape		28.61	kg		
Recycled packaging film (LDPE) for tape		0.94	kg	For 470 rolls of tape	
Polyurethane film required for coating (15 GSM)		169	kg		
Medical grade paper (65 GSM) (Cellulose fiber) for sterilisation Pouch		24.3	kg		
HDPE polyethylene plastic (15 GSM) for sterilisation pouch		6	kg		
Carton Box of recycled Flute material for PPE coverall storage		72.49	kg		
EO gas for PPE sterilisation (EO-CO_2 sterilisation chamber)		14.4	kg		
Carbon Dioxide gas for PPE sterilisation		57.2	kg		
Detergent	Usage stage	1.5	kg		Samsung, India
HDPE polyethylene plastic for storing waste	Treatment stage-Landfill	8	kg		Mathematical model
Caustic Soda	Treatment stage-Incineration	2.82	kg		
Alum		0.84	kg		
Ferric Chloride		0.014	kg		
Electricity/Fuel					
Electricity required for irrigation	Cotton cultivation stage	79.82	kWh		Pers. Comms.
Diesel consumed for land preparation		60.28	kg		Mathematical modelling
Electricity for spinning process (Carding, combing, drawing, roving, winding)	Cotton yarn manufacturing	1818	kWh		Branchetti et al., 2021
Electricity required for recycling of used PET bottles to fiber	Polyester yarn manufacturing	295	kWh		Shen et al., 2010
Electricity required for weaving (wefting and warping)	Polycotton fabric manufacturing	4202.86	kWh		Koç and Kaplan, 2007
Thermal energy required for weaving		2.07	kWh		
Electricity used to recycle 95% of Water by Effluent treatment plant		24.03	kWh		Field Visit
Electricity required to manufacture seam seal tape	Body coverall manufacturing	15	kWh		Same as disposable (Pers. Comms.)
Electricity required for converting the fabric into PPE coveralls (Machinery- CNC cutter, single needle lock stitch or 4/5 thread overlock stitching machine, Hot air seam sealing machine)		271	kWh		
Electricity required for coating		135.2	kWh		
Electricity required for cutting and sealing pouches		18.97	kWh		
Electricity required in sterilisation chamber		240.88	kWh		
Diesel consumed in the round-trip transportation in different processes		0.17	kg	175 km travelled on one side trip	Mathematical model
Electricity required for washing coveralls	Usage stage	67.5	kWh		Assumed for 0.5 kWh per 20 coveralls wash
Diesel consumed on a round-trip (25 + 25 km)	Treatment stage-Landfill	1.55	kg		Mathematical model
Electricity required to run the incineration unit	Treatment stage-Incineration	80.7	kWh		
Diesel consumed to burn the waste		17	kg		
Electricity required to treat water in Effluent treatment plant		8.7	kWh		
Summary of total material input		**1589.88**	**kg**		
Summary of total energy (electricity) input		**7259.73**	**kWh**		
Total fuel input (other than electricity)		79	kg		
Input from Nature					

(*continued on next page*)

Table 3 (*continued*)

Input	Life cycle stage	Quantity	Unit	Note	Source
Land required	Cotton Cultivation	14,000	m^2		Cotcorp, India, 2021
Land area required	Treatment stage-Landfill	0.045	m^2	Similar to disposable	
Summary of total land input		**14000.05**	$\mathbf{m^2}$		
Irrigation water consumption (Irrigation pump)	Cotton Cultivation	15,02,173	l		NABARD, 2018
Water required for wet processing of the fabric	Polycotton fabric manufacturing	29,084	l	95% of this is recycled water and 5% is freshwater every day	Pers. Comms.
Water used in laundering	Usage stage	8807.5	l		
Total water utilised in quencher chamber	Treatment stage-Incineration	10,000	l		Pers. Comms.
Summary of total water input		**1,550,065**	**l**		

(according to the transportation model), so it had very few emissions and its impacts were not studied individually.

In the EoL phase, the common disposal scenarios of the coverall *viz*. Scenario A: landfill and Scenario B: incineration were considered and compared with the P_{Life} phase individually. This helped in quantifying the individual impacts and emissions from both the disposal pathways *i. e.* landfill and incineration and establishing a comparative assessment between both the coveralls from its P_{Life} phase (cradle) to its EoL phase (grave). This gave a comprehensive environmental and human health impact footprint for the different impact indicators considered in the study for attaining a sustainable decision.

4.2. *Mid-point impact results and discussion*

The mid-point impact results of the selected 6 impact categories are given in Table 4 and discussed separately. It is important to note that all the mid-point impact values for the reusable PPE namely in the phases $P_{Life}2$, I2 and L2 stages have been divided by 15 to draw a comparative assessment of single usage of reusable PPE with the single usage of disposable PPE. One reusable PPE undergoes 15 washing cycles (15 times usage) before its final disposal as it loses its protective properties (Thakur et al., 2021). Therefore, despite having high input quantities in the reusable PPE coverall manufacturing, it is still lesser compared to disposable coverall since the former undergoes 15 washing cycles.

4.2.1. *Global Warming Potential (GWP)*

The GWP quantifies the integrated radiative forcing increase of GHGs(Huijbregts et al., 2017) that is released during a particular process, stage or input of the life cycle and contributes to climate change. Results revealed that disposable PPE coveralls have a higher GWP than reusable ones in all the life cycle phases (Table 4). A study by (Cornelio A et al., 2022) also suggests that fabric PPE material have lower CO_2 emissions compared to surgical (plastic-based) material. It may be due to the extraction of polypropylene granulate from fossil fuel-based resources, which involves acquiring propylene gas, compressed air, and energy in the P_{Life} phase. Using injection molding, pellets are formed using huge amounts of energy and heat (Mannheim and Simenfalvi, 2020), which contributes to significant environmental emissions. The primary source of electricity used during the manufacturing of fabric and coveralls is the fossil fuel-based energy of the Southern grid India, which leads to heavy emissions. In landfills, the emissions are due to the release of methane from prolonged plastic waste persisting in the environment (Silva et al., 2021; Kutralam-Muniasamy et al., 2022) while the cotton PPE waste will release biogas in the landfills. Further, in the incineration stage, the high GWP of the disposable coverall is because plastic releases heavy emissions during incineration (Zhao et al., 2009) compared to the polycotton fabric due to toxic coatings, dyes, and chemicals in the plastic-based coverall. Diesel-based transportation also leads to GHGs emissions at all stages.

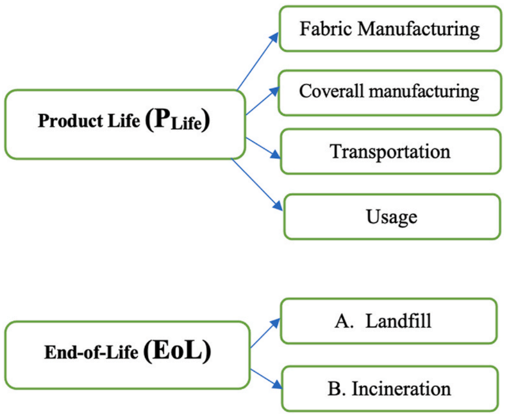


Fig. 5. Categorisation of different life cycle stages into two key phases.

4.2.2. *Terrestrial Acidification*

Terrestrial acidification is a phenomenon where the soil becomes acidic due to the deposition of nutrients like nitrogen oxides, ammonia, and sulfur dioxide in acidic states and several other chemicals and pesticides that lowers the pH of the soil (Azevedo et al., 2013). The disposable PPE has a higher value compared to the reusable one since plastic-based PPE coveralls has various chemical additives, flame retardants, and toxic monomers present in them which disintegrate in the landfill thus leaching into the soil and polluting the groundwater over time (Kutralam-Muniasamy et al., 2022). Although the chemical fertilisers like N, P, K and pesticides (Azevedo et al., 2013) used during the cotton cultivation stage of reusable PPE manufacturing also contribute to the acidifying of the soil.

4.2.3. *Freshwater Eutrophication*

The results for freshwater eutrophication are very low in the range of (0–2 kg P eq.) for all the phases (Table 4). However, disposable PPE coveralls shows a comparatively higher freshwater eutrophication potential than reusable coveralls in the P_{life} phase. The reason could be the accumulation of plastic-based PPE wastes in water bodies due to improper disposal (Ray et al., 2022) and the leaching of microplastics, chemical additives such as plasticisers, UV stabilisers, flame retardants, phthalates, antioxidants, organophosphate esters, bisphenols, and other chemical contaminants that chokes the aquatic life and is linked to cause eutrophication (Zhang et al., 2020; Aquatic Life Lab, 2018). In trace amounts, the toxins become bioavailable to organisms, entering the food chain of humans when seafood is consumed (Kutralam-Muniasamy et al., 2022). In addition, effluents from incineration wastewater treatment plants and the manufacturing industries can also lead to eutrophication in the water bodies (Aquatic Life Lab, 2018). However, in the reusable coverall manufacturing phase, the N and P rich chemical fertilisers used in cotton cultivation stage also cause significant eutrophication.

Table 4

Mid-point impact results for P_{Life}, Landfill, and Incineration stages of disposable and reusable PPE.

Impact category	Unit	P_{Life} 1	P_{Life} 2	I1	I2	L1	L2
Global warming potential	kg CO_2 eq	4673.7	714.2	1342.5	89.5	10.1	0.7
Terrestrial acidification	kg SO_2 eq	13.4	2.5	0.5	0.04	0.02	0
Freshwater eutrophication	kg P eq	1.26	0.35	0.08	0.01	0	0
Terrestrial ecotoxicity	kg 1,4-DCB	3862.9	1305.8	126	8.4	6.5	0.4
Human carcinogenic toxicity	kg 1,4-DCB	145	29	7	0.5	0.19	0.02
Water consumption	m^3	38.12	91	10.8	0.7	0.03	0

Note: P_{Life}1 is disposable PPE Product Life, P_{Life}2 is reusable PPE Product Life, I1 is Incineration of disposable PPE, I2 is Incineration of reusable PPE, L1 is Landfill of disposable PPE, L2 is Landfill of reusable PPE.

4.2.4. *Terrestrial Ecotoxicity*

A disposable coverall during its P_{Life} phase releases chemical additives such as plasticisers, UV stabilisers, flame retardants, phthalates, antioxidants, organophosphate esters, bisphenols, and other endocrine disrupting chemicals, which pose a threat to environment as toxic leachates (Kutralam-Muniasamy et al., 2022), therefore they have a higher ecotoxicity potential to land organisms compared to their reusable counterparts' P_{Life} phase (Table 4). The PPE's chemical additives and toxic monomers disintegrate in the landfill, thus leaching into the soil and polluting the groundwater over time (Kutralam-Muniasamy et al., 2022). Monsoon rains lixiviate the leachates of solid waste, containing hazards such as primary nitrogen, pharmaceuticals, organic compounds, and heavy metals residues. On average, overburdened landfills across the globe can leach up to 5 m^3 ha^{-1} d^{-1} toxins. Disposal of contaminated PPE waste in landfills is fatal to overwintering birds and other organisms reliant on landfill waste for their food. Various seagull species hovering over these landfills have shown decreased reproductivity and chemical toxicity (Silva et al., 2021). The incineration phase of the plastic-based coverall is also very lethal to terrestrial organisms as they inhale the toxic gas.

4.2.5. *Human Carcinogenic Toxicity*

The plastic industry utilises several chemical substances and additives mentioned above which are highly carcinogenic to human health. In the unit of 1,4-dichlorobenzene (DCB), polypropylene coveralls exhibit higher carcinogenic activity than polycotton coveralls (Table 4). Benzene is used by some plastic manufacturing industries to produce plastic pellets, resins, and chemicals. UV stabilisers, flame retardants, phthalates, antioxidants, and polychlorinated biphenyls are highly carcinogenic components used in disposable coveralls (Kutralam-Muniasamy et al., 2022). The sterilisation of PPE coveralls requires a mixture of Ethylene oxide and carbon dioxide gas which are tremendously carcinogenic in nature (CDC, 2016). During the landfilling stage, the open burning of plastic waste can lead to the release of harmful gases (Silva et al., 2021) that can cause breathability issues and even cancer. When plastic coveralls are burned, persistent organic pollutants like dioxins and furans are also released into the environment, posing a threat to human health (Kutralam-Muniasamy et al., 2022).

4.2.6. *Water Consumption*

Out of the selected mid-point impact categories, water consumption is the only parameter that has a higher value for the reusable PPE body coverall compared to the disposable coverall (Table 4). This has a clearly defined reason behind it. The reusable coverall is made up of cotton-polyester blend fabric and so the cotton fiber in it has huge blue and green water consumption. In the cotton cultivation stage, cotton seeds require a tremendously huge amount of irrigated and rainfed water for their growth and development (Water Footprint India, 2022; NABARD, 2018). As a result, woven fabric processing uses a lot of industrial water for bleaching, dyeing, and washing (Wang et al., 2013), which increases its blue water footprint. Due to its washability nature, the laundering of fabric consumes a lot of tap water which leads to a further spike in the water footprint in the P_{Life}2 stage. The grey water discharged from the laundry pollutes the water bodies and also releases a large amount of microfibers that course their way to the aquatic bodies causing threat (Vassilenko et al., 2021). Compared to reusable fabrics, disposable fabrics are more water-efficient since no water is used for fabric-making. In the incineration stage, recycled water is used in the quencher chamber to wash the smoke produced from burning the PPE waste.

As the results show, disposable plastic PPE has a high potential for environmental threats like GWP, freshwater eutrophication, terrestrial acidification and ecotoxicity, and human carcinogenic potential compared to reusable ones (Table 4). This was due to the release of carbon dioxide and carbon monoxide emissions into the environment from its production processes, starting from raw material extraction, electricity consumption, and transportation of finished products. The harmful chemical additives used in plastic manufacturing and textile processing processes also contributed to the high values of impact indicators for disposable PPE.

On the other hand, the reusable PPE body coveralls showed a better environmental profile except for water consumption, as cotton cultivation and irrigation utilise vast amounts of water. Water is also dominant in the dyeing, washing and bleaching of woven fabric, leading to this increase (Parvin et al., 2020). The dyeing, washing and bleaching process of both coveralls include harmful chemicals and contaminants that pollute the water. This can be improved by removing the effluents and contaminants with appropriate water treatment technology. It was observed from the results that although the impact indicators for cotton-polyester coverall production for the given FU were more compared to the disposable one, reusability with laundry washes reduced the environmental impact considerably on a use basis. As the disposable PPE coveralls will go into waste streams and pollute the environment, the reusable ones will enhance their environmental stability by maximizing its usage to 15–20 times which causes no ill effects (Thakur et al., 2021).

For lower water consumption and low toxicity in the soil, there is a need to shift to organic cotton cultivation, where micro-irrigation and organic fertilizers are used without pesticides. The polyester fibre used in the reusable woven fabric should be sourced from recycled PET bottles to give a win-win solution by solving the plastic litter problem and producing durable polyester fibre. The weaving processes like spinning, weaving, etc., require electricity that can be sourced from renewable sources to make it sustainable, as shown in the Sensitivity scenario analysis with 100% Solar PV installation. In the incineration phase, energy recovery technologies may be installed to generate electricity from the burning of waste. Reusable body coveralls can be a sustainable option for consumers, healthcare facilities and policymakers to encourage environmental best practices.

4.3. *Dominant impact indicators in the life cycle of the products*

By comparing the prevalence of the given mid-point impact indicators in different life cycle phases of the two products, it was found that two impact parameters dominated all the life cycle phases *viz*. The GWP and the terrestrial ecotoxicity (Table 4). The possible reason behind this is that the P_{Life} and incineration phases have intensive electricity demand which comes from the fossil fuel-based energy source. This produces a huge amount of emissions and GHGs into the atmosphere which increases the carbon footprint. Terrestrial ecotoxicity is also a dominant impact of the life cycle because the P_{Life} phase of both the disposable and reusable PPE coverall utilise an abundant amount of plastic in packaging, fabric manufacturing, laminating, coating, etc. Which releases toxic chemicals, leachates, and microplastics in the environment which directly disrupts the food web system of the organisms. The ecosystem and its floral and faunal life get disturbed due to the emissions and waste from the coverall production (De-la-Torre and Aragaw, 2021) and its fate in the waste streams.

Further, the result of the fourth phase of LCA, *i.e.*, the interpretation phase including sensitivity and contribution analyses are discussed below.

4.4. Sensitivity analysis-scenario of 100% solar PV grid substitution

The results of the present LCA study could be influenced by a number of input parameters such as electricity demand, water demand, as well as chemical demand which are very high in their life cycle stages as we discussed above. There are several input parameters throughout the life cycle like polypropylene granulates, LDPE packaging films, EO gas, and EVA glue which are polluting in nature but are considerably lower compared to the sensitivity of the electricity used. It is evident from the inventory that electricity demand is significant in all the life cycle stages and as it is from the conventional fossil fuel source, it is also polluting in nature. Therefore, a sensitivity analysis is performed by considering an alternative scenario where the conventional electricity input is replaced by 100% solar PV-based electricity (Figs. 6 and 7).

To understand the share of energy type being contributed in each life cycle stage, the CED was performed which shows that energy is the most sensitive input parameter which is causing these impact indicators to increase. This is further proved by the contribution analysis in the later section.

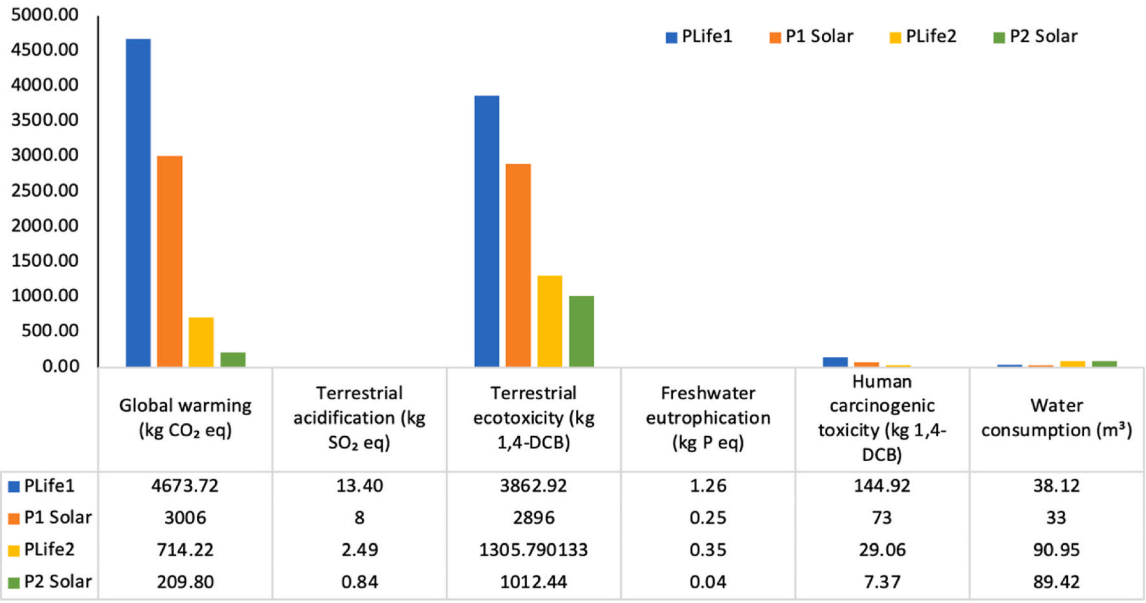
4.5. Cumulative Energy Demand (Lower Heating Value, LHV)

The CED method of impact assessment (Supplementary file Table 8) shows the baseline data of different energy shares for the operation of the cradle-to-grave life cycle stages of the disposable and reusable PPE coverall, where the maximum share of the electricity demand was fulfilled by the conventional, non-renewable, fossil fuel-based energy which is the most polluting source of energy. This was followed by non-renewable nuclear and renewable hydro energy sources. The least share of energy sources was coming from renewable solar energy which is very efficient in nature and less polluting compared to the fossil fuel energy type.

So, to understand the change in the impact potentials with the change in energy source, a scenario analysis is done by substituting the conventional fossil fuel grid electricity input with 100% solar PV energy input (Supplementary file Table 9) using the database required for this analysis from Ecoinvent. The solar PV is made up of Polycrystalline material and it is assumed that high voltage 20 MW energy is being generated from solar towers to power the huge textile industries. The solar PV scenario analysis was done for just the P_{Life} (Fig. 6) and the incineration phase (Fig. 7) and not the landfill phase, as only the previous two consume electricity.

The scenario analysis for the P_{Life} phase depicts that 100% solar energy substitution in the electricity grid can potentially decrease the major environmental and human health impacts by a considerable amount. Solar energy is a renewable source of energy that is far more sustainable in nature than non-renewable fossil fuel energy. And it shows a considerable dip in the GWP because solar energy hardly produces GHGs emissions unlike in the case of fossil energy which is very polluting to the environment. The ecosystem flora and fauna will also benefit from this as there will be lesser pollution and toxic contaminants in the environment.

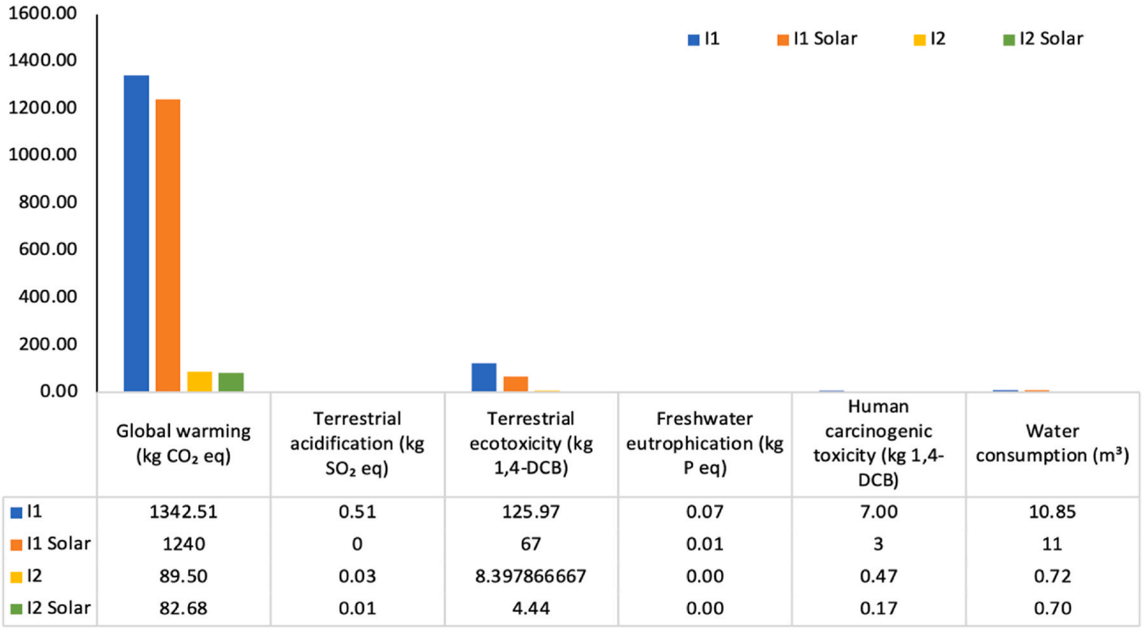
Same is the case with the incineration phase which is a highly



	Global warming (kg CO_2 eq)	Terrestrial acidification (kg SO_2 eq)	Terrestrial ecotoxicity (kg 1,4-DCB)	Freshwater eutrophication (kg P eq)	Human carcinogenic toxicity (kg 1,4-DCB)	Water consumption (m^3)
🟦 PLife1	4673.72	13.40	3862.92	1.26	144.92	38.12
🟧 P1 Solar	3006	8	2896	0.25	73	33
🟨 PLife2	714.22	2.49	1305.790133	0.35	29.06	90.95
🟩 P2 Solar	209.80	0.84	1012.44	0.04	7.37	89.42

Note: PLife1 is disposable PPE Product Life stage with conventional energy, P1 solar is disposable PPE Product Life stage with solar energy, PLife2 is reusable PPE Product Life stage with conventional energy, P2 solar is reusable PPE Product Life stage with solar energy

Fig. 6. Comparative impacts of conventional energy and 100% solar PV in the P_{Life} phase of both the coveralls
Note: PLife1 is disposable PPE Product Life stage with conventional energy, P1 solar is disposable PPE Product Life stage with solar energy, PLife2 is reusable PPE Product Life stage with conventional energy, P2 solar is reusable PPE Product Life stage with solar energy.



	Global warming (kg CO_2 eq)	Terrestrial acidification (kg SO_2 eq)	Terrestrial ecotoxicity (kg 1,4-DCB)	Freshwater eutrophication (kg P eq)	Human carcinogenic toxicity (kg 1,4-DCB)	Water consumption (m^3)
I1	1342.51	0.51	125.97	0.07	7.00	10.85
I1 Solar	1240	0	67	0.01	3	11
I2	89.50	0.03	8.397866667	0.00	0.47	0.72
I2 Solar	82.68	0.01	4.44	0.00	0.17	0.70

Note: I1 is disposable PPE incineration stage with conventional energy, I1 solar is disposable PPE incineration stage with solar energy, I2 is reusable PPE incineration stage with conventional energy, I2 solar is reusable PPE incineration stage with solar energy

Fig. 7. Comparative impact of conventional energy and 100% solar PV in the incineration phase of both the coveralls
Note: I1 is disposable PPE incineration stage with conventional energy, I1 solar is disposable PPE incineration stage with solar energy, I2 is reusable PPE incineration stage with conventional energy, I2 solar is reusable PPE incineration stage with solar energy.

polluting life cycle stage among all. The incineration facility utilises a significant amount of electricity for burning the waste in the chamber and autoclaving and disinfecting the infectious biomedical waste. It consumes electricity for running the Effluent treatment plant for recycling of wastewater. Substitution of fossil-based energy with Solar energy will prove beneficial for the environment and will report fewer emissions. Energy recovery incineration facilities are also a sustainable and environmentally beneficial option compared to those without energy recovery (Zhao et al., 2009). Many incineration facilities in India are based on the energy recovery mechanism of incinerating biomedical waste.

4.6. Contribution analysis

This contribution analysis shows the impact of different input parameters in each life cycle stage on environmental and human health. Input or process contributions to the overall impact assessment were cut off at 5%. Among the resources studied, electricity contributes 75% on average to each of the impact categories studied ($P_{Life}1$, L1, I1) and disposable ($P_{Life}2$, L2, I2). Deionised tap water is the second most polluting resource after groundwater. Reusable PPE coveralls have a water consumption potential of 1%. In the P_{Life} phase, water consumption was identified as the most significant contributing factor for the reusable coverall, yet the software did not consider irrigation groundwater data input. Thus, the software did not account for irrigation groundwater consumption in the other inputs at this stage, which brought the total contribution to 90.89%. Only the contribution of deionised tap water was depicted in the analysis. The reason for the same might be that the land and groundwater themselves are not polluting sources, but when we manipulate them through anthropogenic uses, then these natural resources get interrupted. Therefore, the natural inventory is maybe not be considered by the software in the contribution analysis. Other contributing sources of environmental and health decline are polypropylene granulates and LDPE packaging films. Sustainable alternatives should be found for these inputs to lower their contribution to environmental degradation. The contribution analysis Tables for all the 3 phases for each coverall type are included in the Supplementary file Tables 2–7

5. Conclusions

Our dependence on plastic has dramatically increased since past couple of years, as we coursed through the pandemic, causing long term irreversible damage to the environment and degrading human health. The healthcare sector acted as a perpetrator and a victim of environmental pollution. Extensive use of single use plastic-based PPE, especially the body coveralls pose a significant threat to the terrestrial and aquatic ecosystems, given their polluting nature and disposal frequency. While reductions and recyclability are discussed extensively, the option of reusability has not been explored sufficiently among the universal 3Rs principle for plastic waste management in the healthcare sector.

LCA studies to assess the environmental and human health impact profile of individual PPE item like the body coverall is limited primarily due to i) lack of standard protocol for LCA of PPE body coverall, ii) non availability of India-specific inventory in standard database such as Ecoinvent which is Europe centric, iii) Furthermore, collection of required inventories has also been challenging due to the COVID-19 pandemic. Considering these limitations, this study presents a comparative LCA of disposable and reusable PPE body coveralls from a product life-cycle perspective, by developing a comprehensive LCI and framework specific to the Indian context which is novel in nature. It analyses a range of 6 mid-point impact indicators through its cradle-to-grave to draw an environmental sustainability and health benefit comparison between the two types of coveralls.

Result reveals that reusable PPE body coverall has a better environmental and human-health impact profile than disposable coverall, except for water consumption. To further make it a sustainable choice, high water consumption in the cotton cultivation stage of the reusable coverall manufacturing needs to be minimized. The study also presents a hotspot and sensitivity analysis that suggests that further environmental benefits of the PPE could be achieved by replacing conventional electricity input with 100% solar PV for PPE manufacturing and treatment stages. The study reiterates that it is paramount we shift our course from plastics and explore the option of reusability, thus closing the loop of circular economy. It will further strengthen SDG 12 of the 2030 sustainable development goals that focuses on ‘Responsible Consumption and Production’. The findings will help the medical textile industries, HCWs, and policymakers to make an environmentally informed choice, especially in the crucial time of pandemic.

CRediT authorship contribution statement

Snigdha: Conceptualization, Data curation, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Moonmoon Hiloidhari:** Supervision, Formal analysis, Methodology, Software, Writing – review & editing. **Somnath Bandyopadhyay:** Supervision, Formal analysis, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136166.

References

Aquatic Life Lab, 2018. Contaminants and Eutrophication. http://www.aquaticlifelab.eu/4-7-contaminants-and-eutrophication/. (Accessed 20 October 2022).

Ardente, F., Cellura, M., 2012. Economic allocation in life cycle assessment. J. Ind. Ecol. 16, 387–398. https://doi.org/10.1111/j.1530-9290.2011.00434.x.

Azevedo, L.B., van Zelm, R., Hendriks, A.J., Bobbink, R., Huijbregts, M.A.J., 2013. Global assessment of the effects of terrestrial acidification on plant species richness. Environ. Pollut. (Amsterdam, Neth.) 174, 10–15. https://doi.org/10.1016/j.envpol.2012.11.001.

Batterman, S., World Health Organization. Water, Sanitation and Health Team, 2004. Findings on an Assessment of Small-Scale Incinerators for Health-Care Waste/S. Batterman. World Health Organization. Doc. No. WHO/SDE/WSH/04.07. 77. https://apps.who.int/iris/handle/10665/68775.

BCI, 2020. Better Cotton Initiative. Measuring Cotton Consumption: BCI Conversion Factors and Multipliers. https://bettercotton.org/wp-content/uploads/2020/10/BCI-Conversion-Factors-Multipliers_Oct-2020-1.pdf. (Accessed 20 May 2022).

Boucher, J., Billard, G., Simeone, E., Sousa, J., 2020. The Marine Plastic Footprint. Gland, Switzerland. IUCN. https://doi.org/10.2305/IUCN.CH.2020.01 viii+69 pp.

Branchetti, S., Petrovich, C., Ciaccio, G., De Sabbata, P., Frascella, A., Nigliaccio, G., 2021. Energy efficiency indicators for textile industry based on a self-analysis tool. In: International Conference on Smart Cities and Green ICT Systems, International Conference on Vehicle Technology and Intelligent Transport Systems. Springer, Cham, pp. 3–27. https://doi.org/10.1007/978-3-030-68028-2_1.

CDC, 2016. Centers for Disease Control and Prevention. Ethylene Oxide “Gas” Sterilisation. https://www.cdc.gov/infectioncontrol/guidelines/disinfection/sterilization/ethylene-oxide.html. (Accessed 21 May 2022).

CDC, 2020. Centers for Disease Control and Prevention. Optimising Personal Protective Equipment (PPE) Supplies. https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/index.html. (Accessed 21 May 2022).

Cornelio, A., Zanoletti, A., Federici, S., Ciacci, L., Depero, L.E., Bontempi, E., 2022. Environmental impact of surgical masks consumption in Italy due to COVID-19 pandemic. Materials 15, 2046. https://doi.org/10.3390/ma15062046.

Cpcb, 2021. Central Pollution Control Board. Annual Report on Biomedical Waste Management as Per Biomedical Waste Management Rules 2016. https://cpcb.nic.in/uploads/Projects/Bio-Medical-Waste/AR_BMWM_2020.pdf. (Accessed 20 May 2022).

De-la-Torre, G.E., Aragaw, T.A., 2021. What we need to know about PPE associated with the COVID-19 pandemic in the marine environment. Mar. Pollut. Bull. 163, 111879 https://doi.org/10.1016/j.marpolbul.2020.111879.

Dharmaraj, S., Ashokkumar, V., Hariharan, S., Manibharathi, A., Show, P.L., Chong, C.T., Ngamcharussrivichai, C., 2021. The COVID-19 pandemic face mask waste: a blooming threat to the marine environment. Chemosphere 272, 129601. https://doi.org/10.1016/j.chemosphere.2021.129601.

Do Thi, H.T., Mizsey, P., Toth, A.J., 2021. Applicability of membranes in protective face masks and comparison of reusable and disposable face masks with life cycle assessment. Sustainability 13, 12574. https://doi.org/10.3390/su132212574.

European Parliament, 2019. Environmental Impact of the Textile and Clothing Industry. European Parliamentary Research Service. Members’ Research Service PE 633.143. https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/633143/EPRS_BRI(2019)633143_EN.pdf.

Hasanbeigi, A., Price, L., 2012. A review of energy use and energy efficiency technologies for the textile industry. Renew. Sustain. Energy Rev. 16, 3648–3665.

Hicks, A., Temizel-Sekeryan, S., Kontar, W., Ghamkhar, R., Morris, M.R., 2021. Personal respiratory protection and resiliency in a pandemic, the evolving disposable versus reusable debate and its effect on waste generation. Resour. Conserv. Recycl. 168, 105262 https://doi.org/10.1016/j.resconrec.2020.105262.

Hiloidhari, M., Banerjee, R., Rao, A.B., 2021. Life cycle assessment of sugar and electricity production under different sugarcane cultivation and cogeneration scenarios in India. J. Clean. Prod. 290, 125170 https://doi.org/10.1016/j.jclepro.2020.125170.

Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Karim, N., Afroj, S., Lloyd, K., Oaten, L.C., Andreeva, D.V., Carr, C., Farmery, A.D., Kim, I.D., Novoselov, K.S., 2020. Sustainable personal protective clothing for healthcare applications: a review. ACS Nano 14, 12313–12340. https://doi.org/10.1021/acsnano.0c05537.

Klemeš, J.J., Fan, Y.V., Tan, R.R., Jiang, P., 2020. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. Renew. Sustain. Energy Rev. 127, 109883 https://doi.org/10.1016/j.rser.2020.109883.

Klemeš, J.J., Fan, Y.V., Jiang, P., 2021. Plastics: friends or foes? The circularity and plastic waste footprint. Energy Sources, Part A Recovery, Util. Environ. Eff. 43, 1549–1565. https://doi.org/10.1080/15567036.2020.1801906.

Koç, E., Kaplan, E., 2007. An investigation on energy consumption in yarn production with special reference to ring spinning. Fibres Text. East. Eur. 15, 18–25.

Kothari, R., Sahab, S., Singh, H.M., Singh, R.P., Singh, B., Pathania, D., Singh, A., Yadav, S., Allen, T., Singh, S., Tyagi, V.V., 2021. COVID-19 and waste management in Indian scenario: challenges and possible solutions. Environ. Sci. Pollut. Res. 28, 52702–52723. https://doi.org/10.1007/s11356-021-15028-5.

Kumar, H., Azad, A., Gupta, A., Sharma, J., Bherwani, H., Labhsetwar, N.K., Kumar, R., 2020. COVID-19 creating another problem? Sustainable solution for PPE disposal through LCA approach. Environ. Dev. Sustain. 23, 9418–9432. https://doi.org/10.1007/s10668-020-01033-0.

Kumar, R., Sharma, P., Bandyopadhyay, S., 2021. Evidence of microplastics in wetlands: extraction and quantification in Freshwater and coastal ecosystems. J. Water Proc. Eng. 40, 101966 https://doi.org/10.1016/J.JWPE.2021.101966.

Kutralam-Muniasamy, G., Pérez-Guevara, F., Shruti, V.C., 2022. A critical synthesis of current peer-reviewed literature on the environmental and human health impacts of COVID-19 PPE Litter: new findings and next steps. J. Hazard Mater. 422, 126945 https://doi.org/10.1016/j.jhazmat.2021.126945.

Liang, Y., Song, Q., Wu, N., Li, J., Zhong, Y., Zeng, W., 2021. Repercussions of COVID-19 pandemic on solid waste generation and management strategies. Front. Environ. Sci. Eng. 15 https://doi.org/10.1007/s11783-021-1407-5.

Mannheim, V., Simenfalvi, Z., 2020. Total life cycle of polypropylene products: reducing environmental impacts in the manufacturing phase. Polymers 12, 1901. https://doi.org/10.3390/polym12091901.

McQuerry, M., Easter, E., Cao, A., 2021. Disposable versus reusable medical gowns: a performance comparison. Am. J. Infect. Control 49, 563–570. https://doi.org/10.1016/j.ajic.2020.10.013.

MoHFW, 2020. Ministry of Health and Family Welfare. https://www.mohfw.gov.in/pdf/GuidelinesonrationaluseofPersonalProtectiveEquipment.pdf. (Accessed 20 May 2022).

NABARD, 2018. Water Productivity Mapping of Major Indian Crops. https://www.nabard.org/auth/writereaddata/tender/1806181128Water%20Productivity%20Mapping%20of%20Major%20Indian%20Crops,%20Web%20Version%20(Low%20Resolution%20PDF).pdf. (Accessed 20 May 2022).

Neto, M.L.R., Almeida, H.G., Esmeraldo, J.D.A., Nobre, C.B., Pinheiro, W.R., de Oliveira, C.R.T., da Costa Sousa, I., Lima, O.M.M.L., Lima, N.N.R., Moreira, M.M., Lima, C.K.T., 2020. When health professionals look death in the eye: the mental health of professionals who deal daily with the 2019 coronavirus outbreak. Psychiatr. Res. 288, 112972 https://doi.org/10.1016/2Fj.psychres.2020.112972.

Nfsm, 2020. National Food Security Mission. Introduction to Cotton. https://www.nfsm.gov.in/BriefNote/BN_Cotton.pdf. (Accessed 20 May 2022).

NIH, 2020. National Institute of Health, USA. Study Suggests New Coronavirus May Remain on Surfaces for Days. https://www.nih.gov/news-events/nih-research-matters/study-suggests-new-coronavirus-may-remain-surfaces-days. (Accessed 21 May 2022).

Palanichamy, C., Babu, N.S., 2005. Second stage energy conservation experience with a textile industry. Energy Pol. 33, 603–609. https://doi.org/10.1016/j.enpol.2003.09.004.

Parvin, F., Islam, S., Akm, S.I., Urmy, Z., Ahmed, S., 2020. A study on the solutions of environment pollution and worker's health problems caused by textile manufacturing operations. Biomed. J. Sci. Tech. Res. 28, 21831–21844. https://doi.org/10.26717/bjstr.2020.28.004692.

PIB, 2020. Press Information Bureau. https://www.pib.gov.in/PressReleseDetailm.aspx?PRID=1680059. (Accessed 20 May 2022).

Ramteke, S., Sahu, B.L., 2020. Novel coronavirus disease 2019 (covid-19) pandemic: considerations for the biomedical waste sector in India. Case. Stud. Chem. Environ. Eng. 2, 100029 https://doi.org/10.1016/j.cscee.2020.100029.

Ray, S.S., Lee, H.K., Huyen, D.T., Chen, S.S., Kwon, Y.N., 2022. Microplastics waste in environment: a perspective on recycling issues from PPE kits and face masks during the COVID-19 pandemic. Environ. Technol. Innovat. 26, 102290 https://doi.org/10.1016/j.eti.2022.102290.

Rizan, C., Reed, M., Bhutta, M.F., 2021. Environmental impact of personal protective equipment distributed for use by health and social care services in England in the first six months of the COVID-19 pandemic. J. R. Soc. Med. 114, 250–263. https://doi.org/10.1177/01410768211001583.

Sharma, H.B., Vanapalli, K.R., Cheela, V.R.S., Ranjan, V.P., Jaglan, A.K., Dubey, B., Goel, S., Bhattacharya, J., 2020. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. Resour. Conserv. Recycl. 162, 105052 https://doi.org/10.1016/j.resconrec.2020.105052.

Shekhar, A.R., Kumar, A., Syamsai, R., Cai, X., Pol, V.G., 2022. Is the plastic pandemic a greater threat to humankind than COVID-19? ACS Sustain. Chem. Eng. 10, 3150–3154. https://doi.org/10.1021/acssuschemeng.1c08468.

Shen, L., Worrell, E., Patel, M.K., 2010. Open-loop recycling: a LCA case study of pet bottle-to-fibre recycling. Resour. Conserv. Recycl. 55, 34–52. https://doi.org/10.1016/j.resconrec.2010.06.014.

Silva, P.A.L., Prata, J.C., Walker, T.R., Campos, D., Duarte, A.C., Soares, A.M.V.M., Barcelò, D., Rocha-Santos, T., 2020. Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. Sci. Total Environ. 742, 140565 https://doi.org/10.1016/j.scitotenv.2020.140565.

Silva, P.A.L., Prata, J.C., Duarte, A.C., Barcelò, D., Rocha-Santos, T., 2021. An urgent call to think globally and act locally on landfill disposable plastics under and after covid-19 pandemic: pollution prevention and technological (bio) remediation solutions. Chem. Eng. J. 426, 131201 https://doi.org/10.1016/j.cej.2021.131201.

Singh, N., Tang, Y., Ogunseitan, O.A., 2020. Environmentally sustainable management of used personal protective equipment. Environ. Sci. Technol. 54, 8500–8502. https://doi.org/10.1021/acs.est.0c03022.

Singh, S.K., Khawale, R.P., Chen, H., Zhang, H., Rai, R., 2021. Personal protective equipments (PPEs) for COVID-19: a product lifecycle perspective. Int. J. Prod. Res. 1–22. https://doi.org/10.1080/00207543.2021.1915511, 0.

Taylor, A.M., Bergman, R.D., Puettmann, M.E., Alanya-Rosenbaum, S., 2017. Impacts of the allocation assumption in life-cycle assessments of wood-based panels. For. Prod. J. 67, 390–396. https://doi.org/10.13073/fpj-d-17-00009.

Thakur, R., Ray, D., Jana, P., 2021. Fabrics for PPE- Face Masks and Body Coverall. https://www.amazon.in/Fabrics-PPE-Face-Mask-Coverall-ebook/dp/B08XBXJFM6. (Accessed 21 May 2022).

The Hindu, 2017. Plastic Bottles Turn Mattresses, Quilts & Much More. https://www.thehindu.com/sci-tech/energy-and-environment/plastic-bottles-turn-mattresses-quilts-much-more/article18714374.ece. (Accessed 22 October 2022).

UNEP, 2020. United Nations Environment Programme. Waste Management during the COVID-19 Pandemic – from Response to Recovery. https://wedocs.unep.org/bitstream/handle/20.500.11822/33416/WMC-19.pdf?sequence=1%26isAllowed=y. (Accessed 19 October 2022).

Van den Berghe, A.J., Zimmer, C., 2011. Life Cycle Assessments of Single-Versus Multiple-Use Surgical Gowns. Minnesota Technical Assistance Program, University of Minnesota, Minneapolis, MN. http://www.sustainabilityroadmap.org/pims/pdfs/pim247_lifecycle_assessment_disposable_versus_reusable.pdf.

Vanapalli, K.R., Sharma, H.B., Ranjan, V.P., Samal, B., Bhattacharya, J., Dubey, B.K., Goel, S., 2021. Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic. Sci. Total Environ. 750, 141514 https://doi.org/10.1016/j.scitotenv.2020.141514.

Vassilenko, E., Watkins, M., Chastain, S., Mertens, J., Posacka, A.M., Patankar, S., Ross, P.S., 2021. Domestic laundry and microfiber pollution: exploring fiber shedding from consumer apparel textiles. PLoS One 16, e0250346. https://doi.org/10.1371/journal.pone.0250346.

Vozzola, E., Overcash, M., Griffing, E., 2020. An environmental analysis of reusable and disposable surgical gowns. AORN J. 111, 315–325. https://doi.org/10.1002/aorn.12885.

Wang, L., Ding, X., Wu, X., 2013. Blue and grey water footprint of textile industry in China. Water Sci. Technol. 68, 2485–2491. https://doi.org/10.2166/wst.2013.532.

Water Footprint India, 2022. Fair and Smart Use of World's Fresh Water. https://waterfootprint.org/en/. (Accessed 21 May 2022).

Zhang, Y., Liang, J., Zeng, G., Tang, W., Lu, Y., Luo, Y., Xing, W., Tang, N., Ye, S., Li, X., Huang, W., 2020. How climate change and eutrophication interact with microplastic pollution and sediment resuspension in shallow lakes: a review. Sci. Total Environ. 705, 135979 https://doi.org/10.1016/j.scitotenv.2019.135979.

Zhao, W., van der Voet, E., Huppes, G., Zhang, Y., 2009. Comparative life cycle assessments of incineration and non-incineration treatments for medical waste. Int. J. Life Cycle Assess. 14, 114–121. https://doi.org/10.1007/s11367-008-0049-1.